MIDDLE EAST TURBOMACHINERY SYMPOSIUM

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Root Cause Analysis of a vibration problem in a propylene turbo compressor

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Problem description

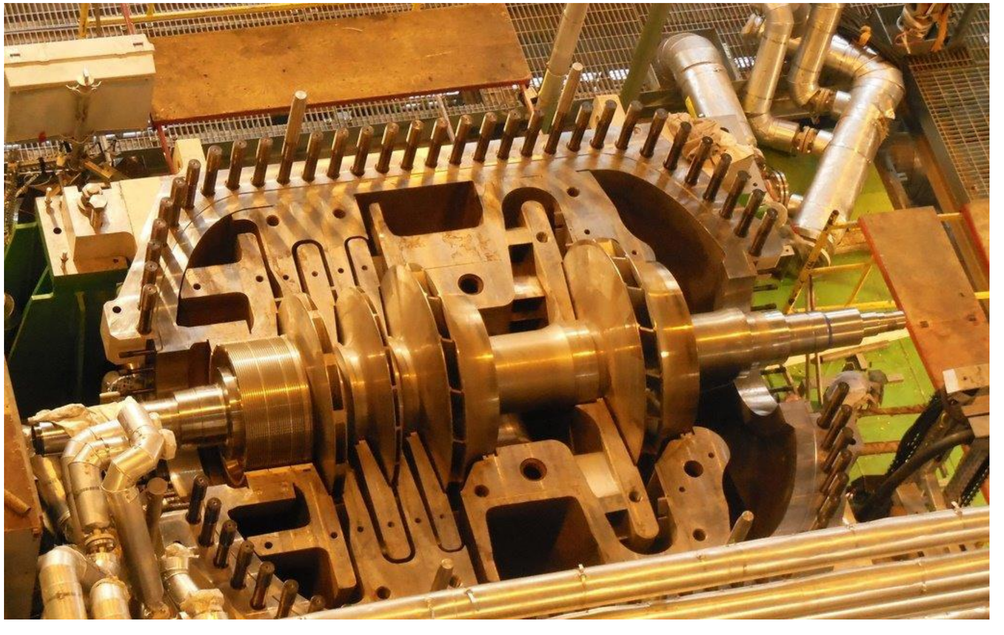
- A newly installed turbo compressor system for propylene showed vibrations in the piping system and rotor.
- After that supporting layout was significantly improved measurements showed that vibrations were within the allowable range.
- Still the rotor vibrations were not acceptable.
- A root cause analysis was carried that showed two likely causes.

The installation

- Large diameter piping (60 inch suction).
- Reducer to 48 inch just upstream of the inlet of the compressor.
- Large flows ~ 1500 tonnes/h (25 m/s).
- Heavy gas ~ 44 kg/kmol @ 6.6 barg.
- 2 phase flow after 2nd stage condenser: liquid separation via large K.O. drum at the suction side (15 m height).

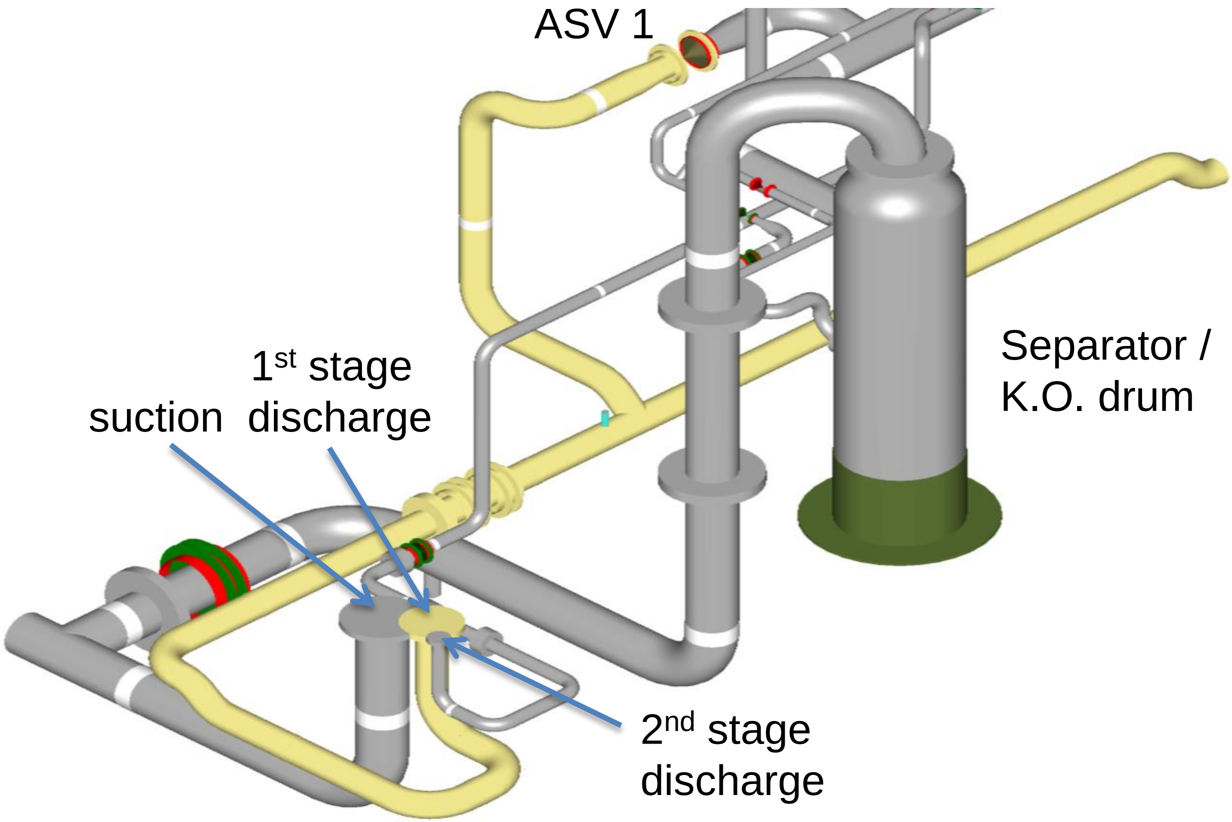
The compressor

- 2 stage radial turbo compressor ~ 2800 rpm & 23 MW (horizontally split).
- 1 inlet and 2 outlets underneath compressor.
- Discharge stages connected with suction via anti-surge valves (ASV 1 and 2).



The installation

- Essential part: separator, suction system, 1st stage discharge (yellow), turbo-compressor.

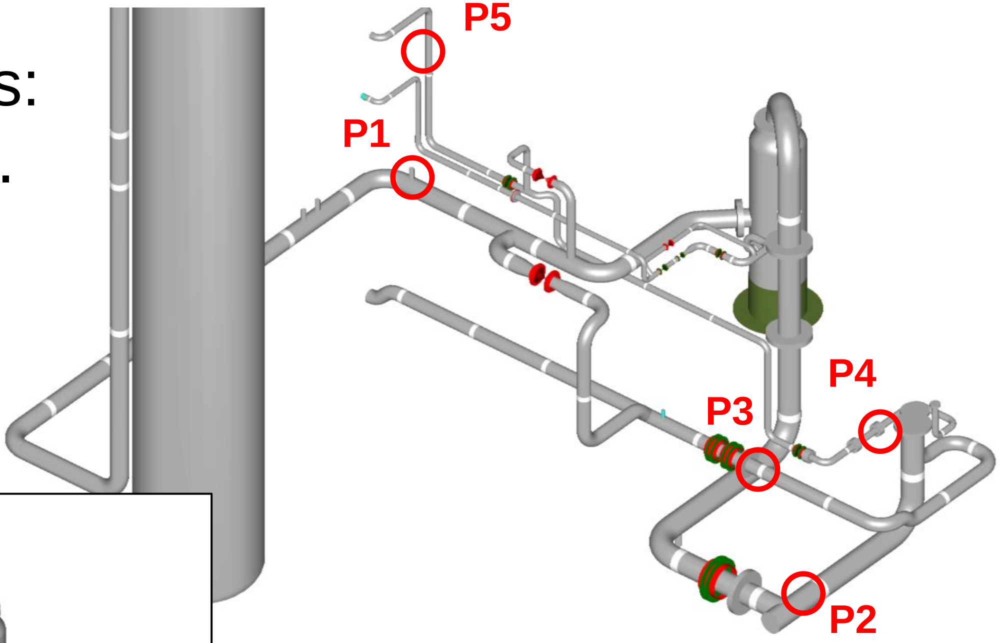


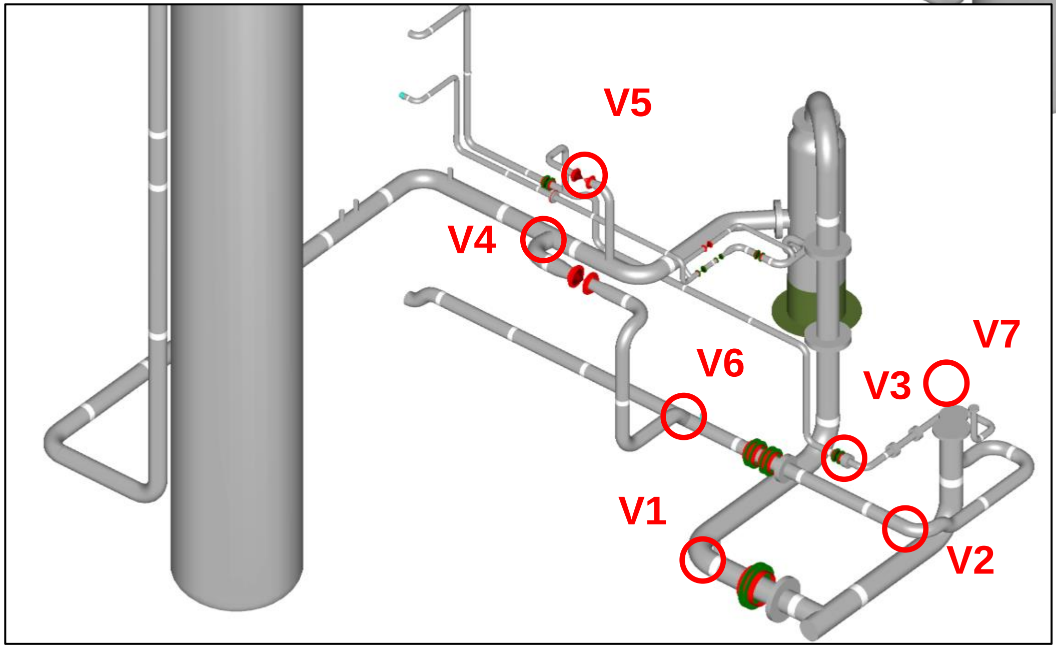
1 - Pipe system design

- Original design did not account for pulsations and vibrations.
- Flexible / spring pipe supports with gaps.
- After first start-up large vibrations.
- Pipe supports have been reinforced significantly.
- Verification measurements showed acceptable vibration levels.
- Rotor vibrations still present.
- Root cause unknown.

Pulsation and vibration measurements

- Fixed measurement points: 5 puls. & 7 vibr. Locations.
- Also measurements with hand held equipment: 27 locations (tri-axial).

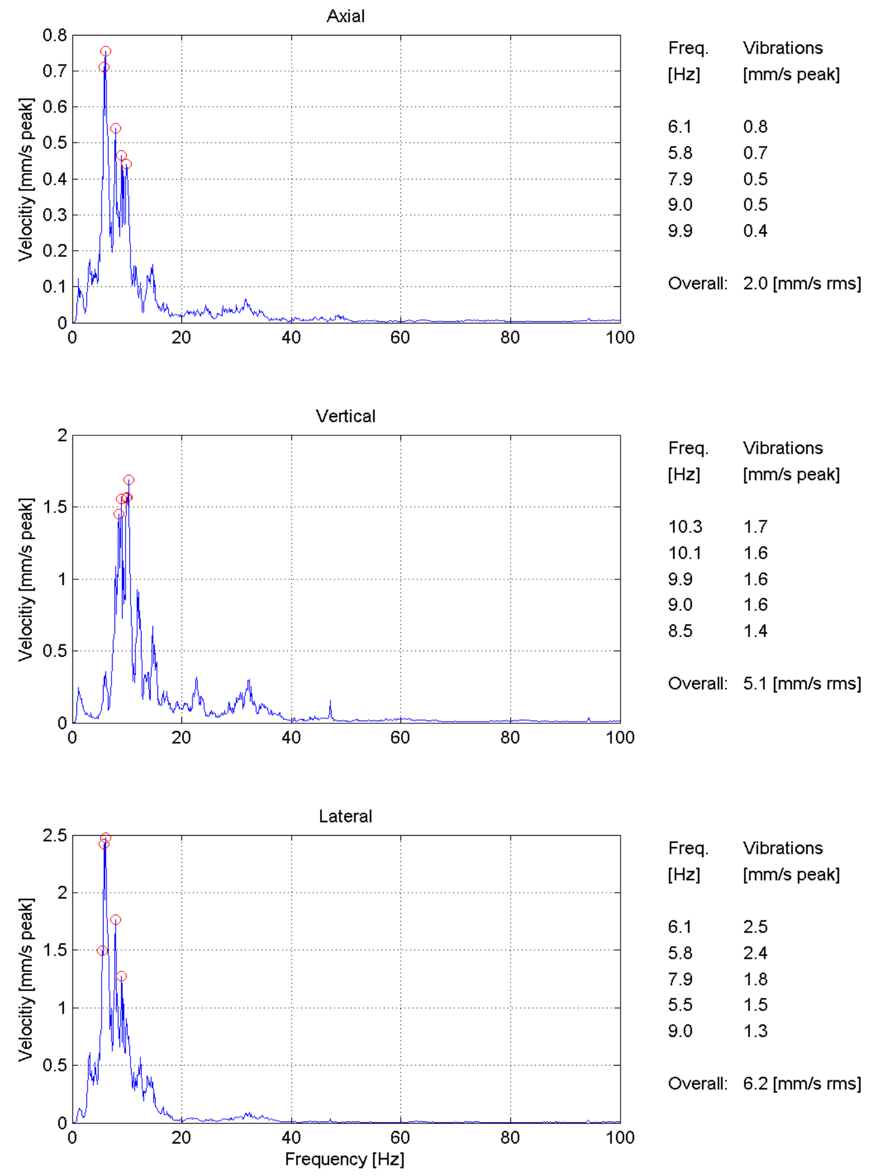




- Measurement program:
- Varying ASV settings.
- Varying RPM / load.

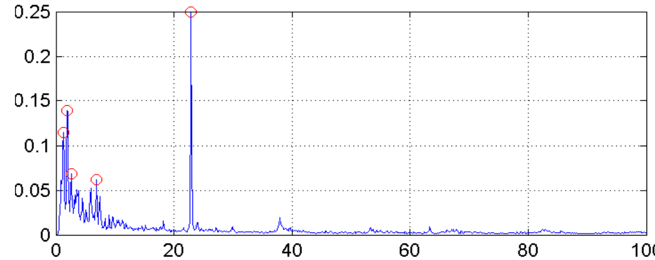
Measured vibrations

- Typical vibration spectra on V2 (close to compressor) show vibrations at low frequencies:
    - 0 – 15 Hz.
    - 20 – 40 Hz.
    - 45 Hz (compr. speed).
- Due to the improved pipe supports vibration levels are acceptable, both displacements and velocities.

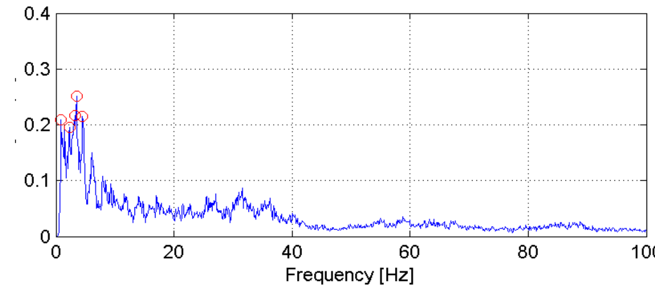


Measured pulsations

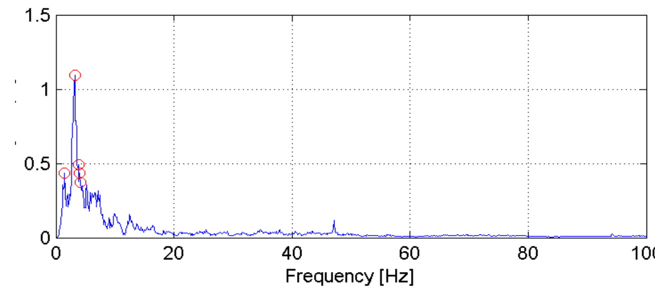
- Typical pressure spectra show acoustic resonances at low frequencies → flow induced pulsations (FIPs).
- Pulsations reach the allowable pulsation levels of API 618 …. For reciprocating compressors!
- Pulsation levels up to approximately 16 kPa → vibration forces in the order of 10 kN on the piping @ 3.2 Hz!



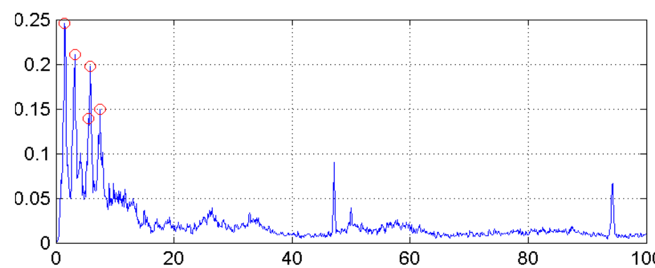
Freq. [Hz]	Pulsations [kPa pk]
22.9	0.25
1.9	0.14
1.3	0.11
2.6	0.07
6.9	0.06
	2.7 [kPa pkpk]



Freq. [Hz]	Pulsations [kPa pk]
3.5	0.25
3.2	0.22
4.5	0.22
0.9	0.21
2.3	0.20
	8.3 [kPa pkpk]



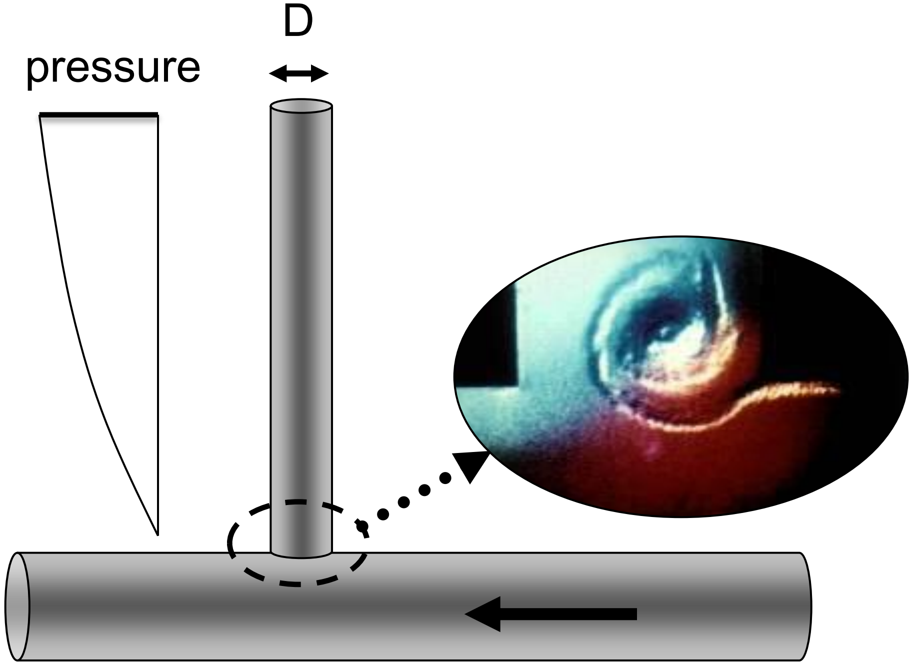
Freq. [Hz]	Pulsations [kPa pk]
3.2	1.09
3.8	0.49
1.5	0.44
4.0	0.43
4.2	0.37
	15.8 [kPa pkpk]



Freq. [Hz]	Pulsations [kPa pk]
1.5	0.25
3.2	0.21
5.8	0.20
7.5	0.15
5.5	0.14
	7.8 [kPa pkpk]

Flow Induced Pulsations

- Pulsations are caused by vortex shedding in a T of a closed side branch.
- The vortex frequency depends linearly on the flow velocity and diameter of the side branch.
- Pulsations are amplified if the vortex frequency is equal to the resonance frequency of the side branch.

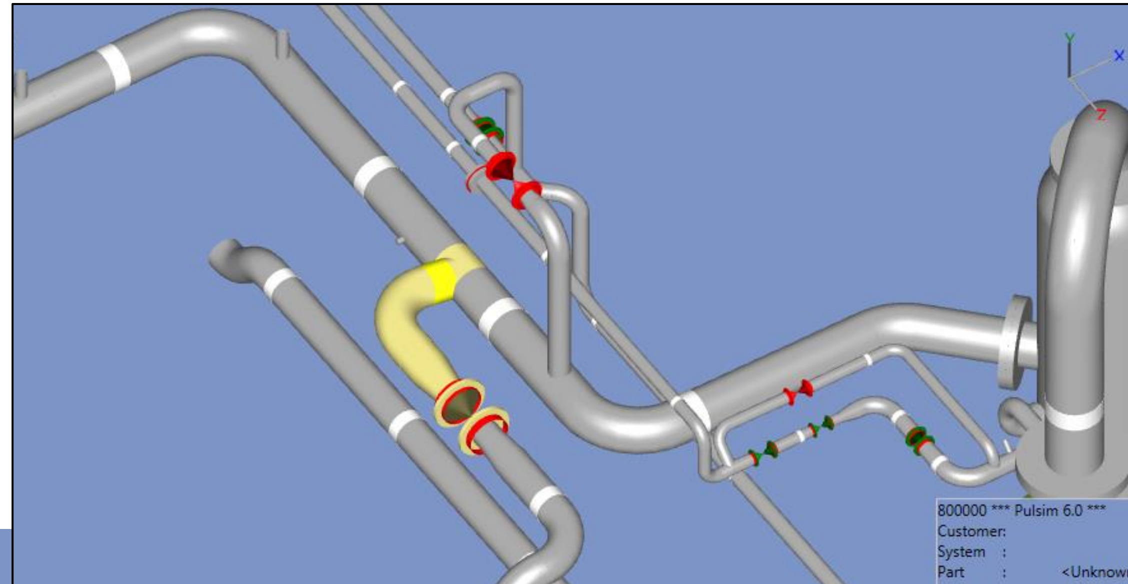


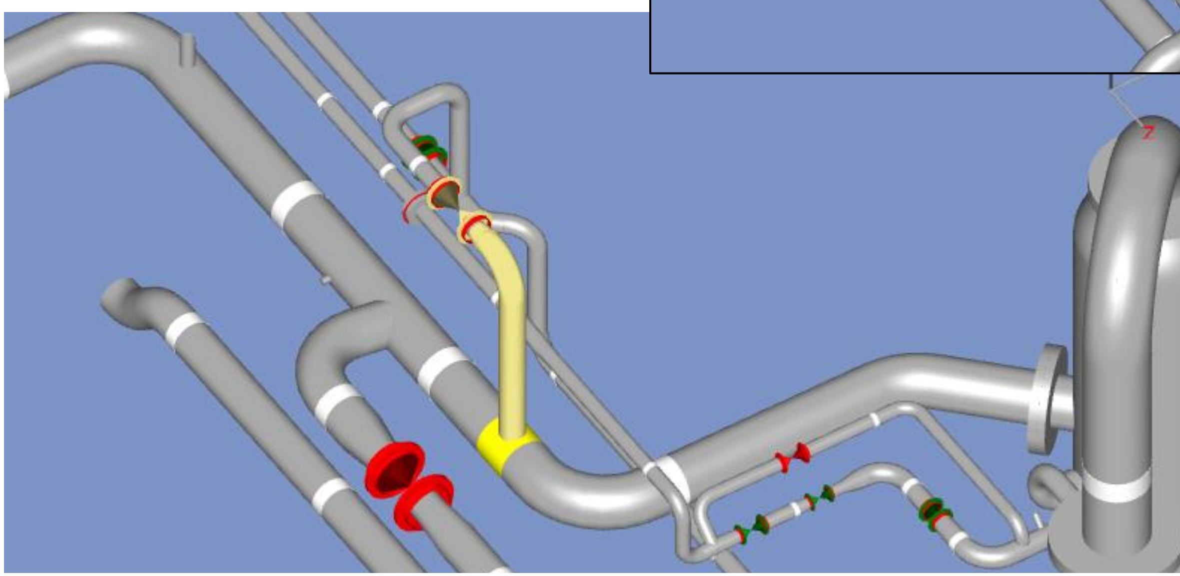
$$f = Sr \cdot \frac{U_0}{D}$$

$$Sr \approx 0.4$$

Flow Induced Pulsations

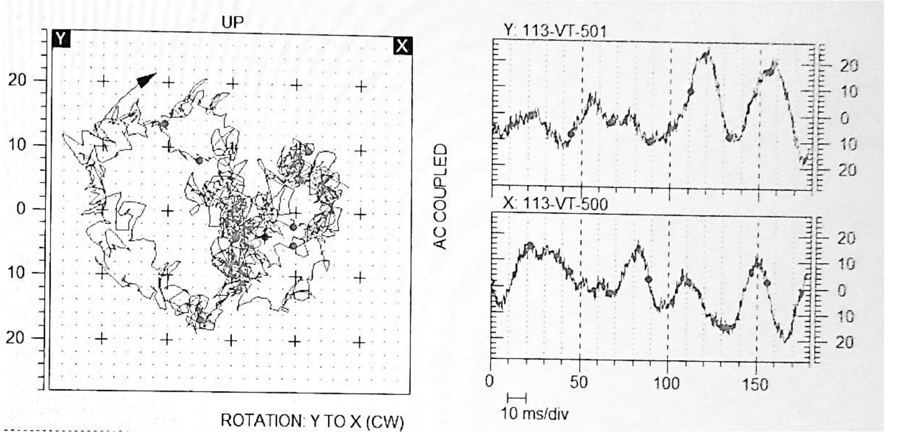
- Examples for the present system:
- 1^{st} and 2^{nd} stage ASV lines, when valves (partially) closed.



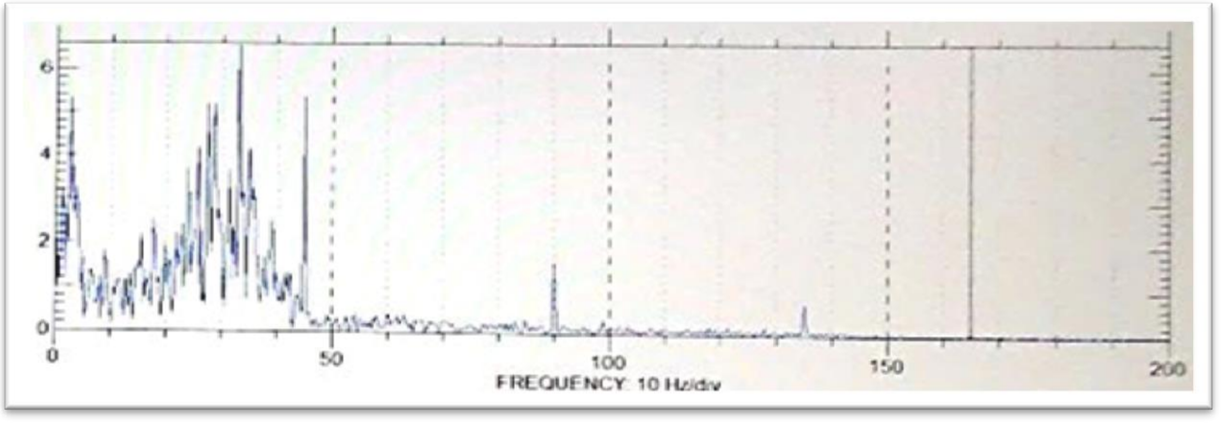


Rotor vibrations

- Proximity probes on rotor show instability in orbits at > 90% load.



- Rotor vibrations have similar frequencies as both the vibrations and pulsations: < 10Hz, **20 – 40 Hz** and 45 Hz.



Typical rotor displacement spectrum

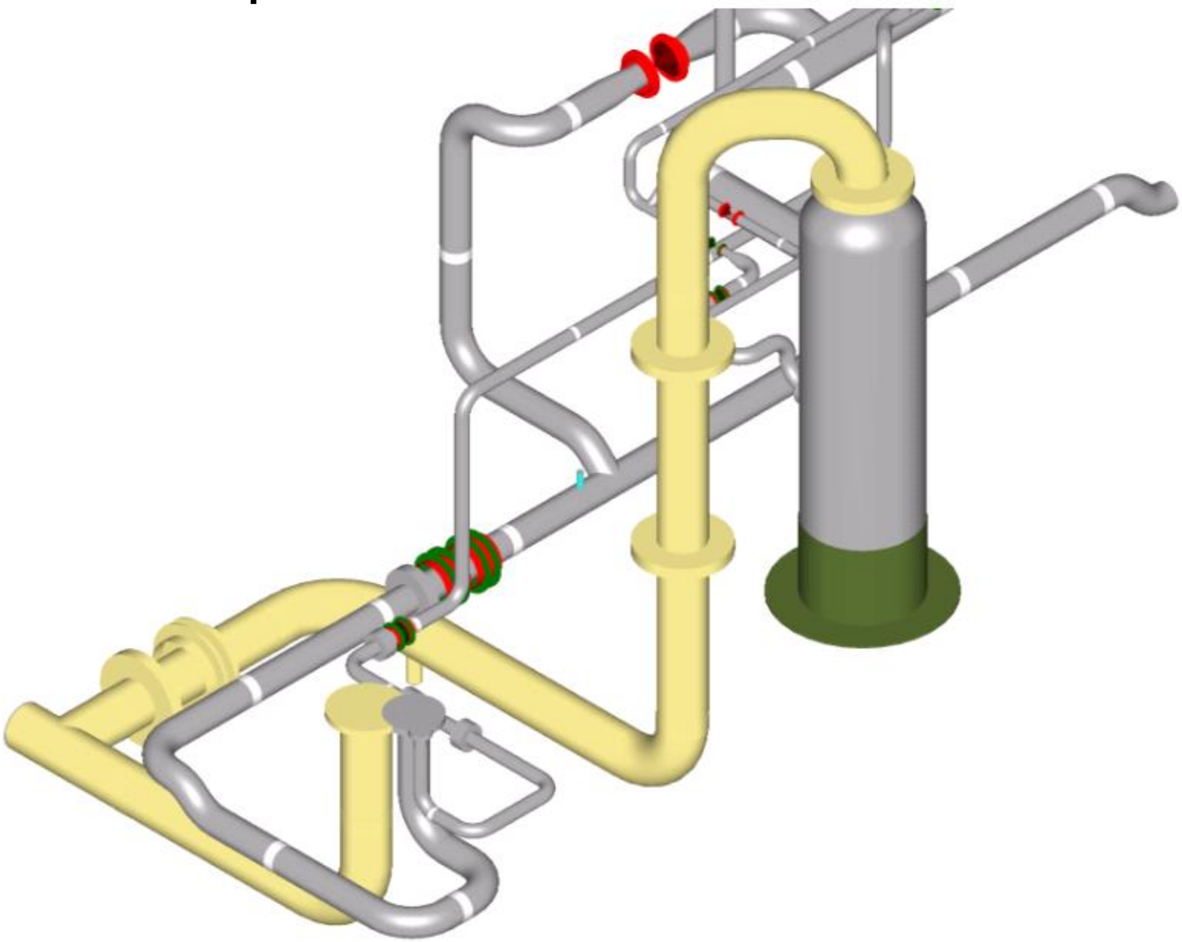
Rotor vibrations

- Although the API617 Level II stability criteria are met (log. dec. >0.1), still high rotor vibration occur.
- First critical of the rotor around 36 Hz (on site mech. run test)
  → first lateral resonance mode excited by a broadband source around this frequency.
- Vibrations in 20-40 Hz range increase with increasing compressor speed / flow.

- A Root Cause Analysis has been made.

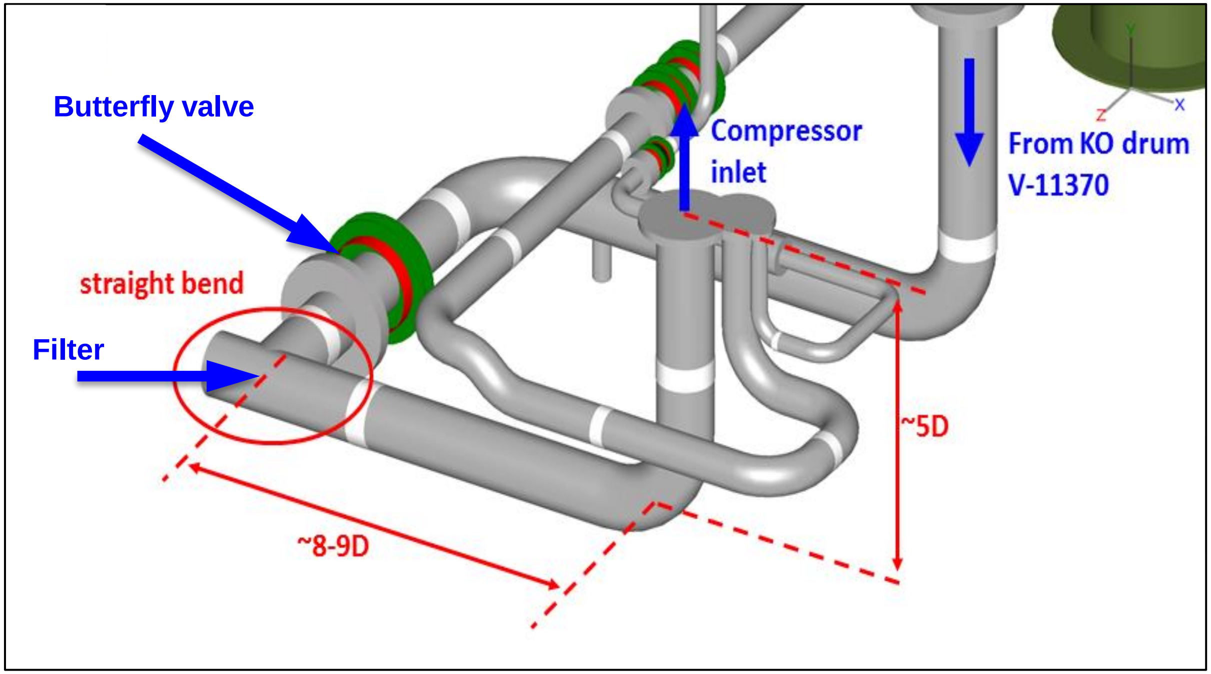
Root Cause Analysis (RCA) rotor vibrations

First: overview suction side compressor, between K.O. drum and compressor inlet:



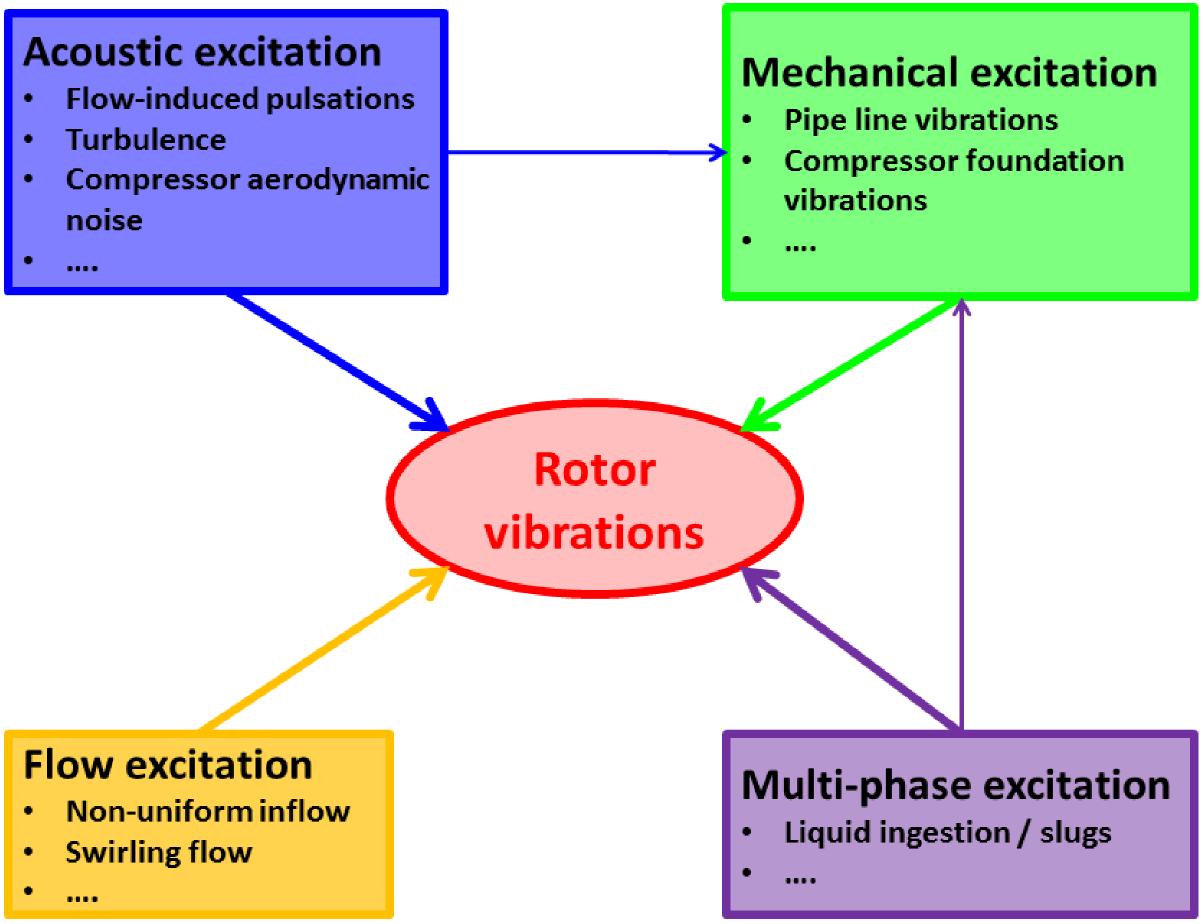
Suction side compressor

- Several <u>out of plane</u> sharp bends in the suction piping.
- Distance between sharp 90 degr. T joint and elbow <10D.
- Distance between elbow and inlet ~5D.
- Filter in T joint.
- Butterfly valve just upstream T joint.
- 60 → 48 inch reduced just before compressor inlet.
- Low point in between K.O. drum and inlet: 20 inch draining boot.



Root Cause Analysis (RCA) rotor vibrations

Schematic of possible mechanisms that can lead to rotor vibrations



RCA matrix

	Mechanism	Description	Mitigation measures	Judgment
1	Acoustic – compressor aerodynamic noise	Tonal, high-frequent excitation, caused by rotor-stator interactions		Unlikely
2	Mechanical – piping vibrations	Connecting piping vibrations exciting the compressor and triggering the rotor instability		Unlikely
3	Mechanical – foundation vibrations	Concrete pedestal vibrations are mechanically exciting the compressor and rotor		Unlikely
4	Rotating stall in the compressor	Flow in impeller gets unstable at a certain load		Unlikely RS occurs at reduced flow
5	Mechanical malfunction in compressor	Run out of clearance → rubbing		Unlikely

RCA matrix

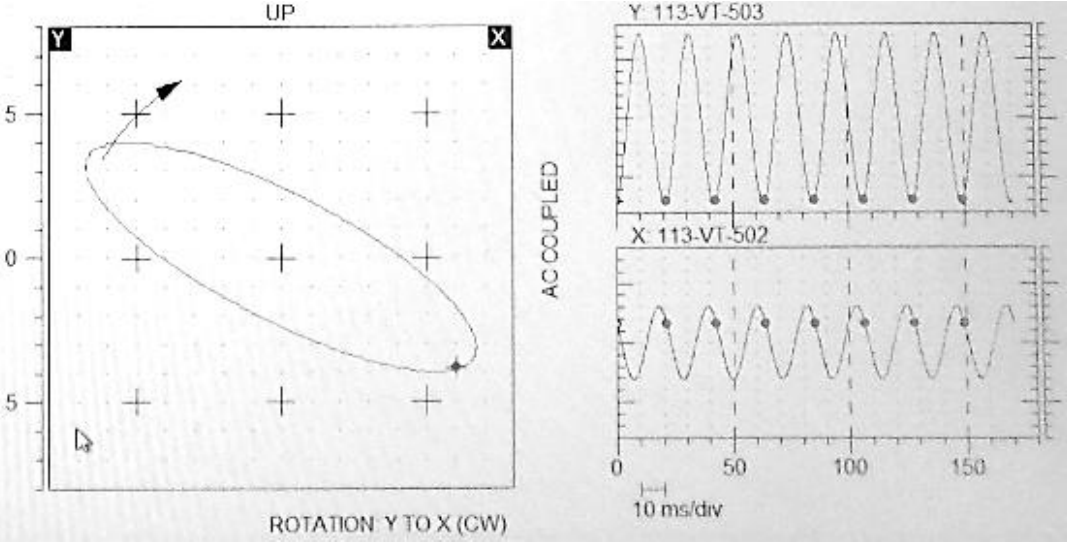
	Mechanism	Description	Mitigation measures	Judgment
6	Acoustic – flow-induced pulsations	Resonance in closed side branch; vortex shedding	Relocation of valve; reduce flow speed in main piping; apply restriction in branch	Likely to occur, but not the critical effect for rotor vibrations
7	Acoustic – pressure fluctuations caused by turbulence in flow	Broad-band, low-frequent excitation of impeller and rotor	Reduce flow speed	Likely
8	Multi-phase excitation – liquid ingestion	Accumulated liquid is entrained into the compressor; varying liquid → unsteady load on the rotor	Improve separator, avoid liquid accumulation in upstream piping; thermal insulation piping	Likely
9	Flow excitation – non uniform inflow	Short radius elbows → varying load on compressor	Apply large radius elbows, flow straightener	Likely
10	Flow excitation – swirling inflow	Double out-of-plane elbows induce swirling flow that may not be re-developed before impacting on the compressor	Increase distance between elbows and compressor, flow straightener	Likely

RCA rotor vibrations

1. Liquid in suction flow.

The internals of the K.O. drum have been modified:

- Liquid carry over to compressor inlet mitigated.
- Compressor now runs stable up to 106% compressor speed!
- Rotor vibration amplitudes still high (50 μm pk-pk). However, this is acceptable according to compressor manufacturer.



RCA rotor vibrations

2. FIPs in combination with flow distortion.

The high vibration amplitudes can be caused by FIPs and flow distortion:

- Sharp bends in the suction piping can induce unsteady flow distortion.
- Double out-of-plane bend will cause (unsteady) swirl in flow.
- Reducer close to compressor inlet can increase flow distortion.

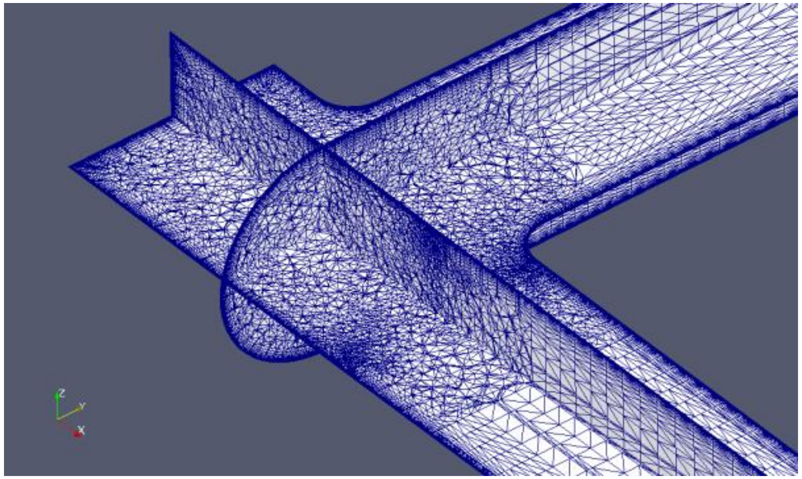
→ CFD analysis compressor inlet section performed.

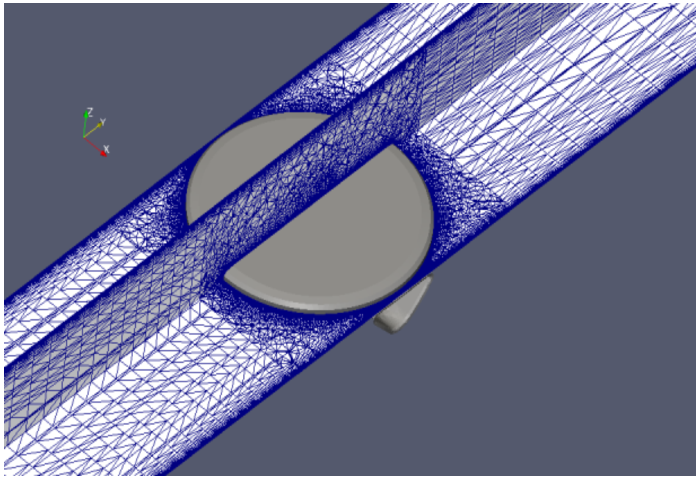
Note: especially combination of rather undamped rotor and flow FIP / distortion can lead to high rotor vibration amplitudes.

RCA rotor vibrations

2. FIPs in combination with flow distortion – CFD analysis.

- High Reynolds number and large geometry dimension require super-fine boundary-layer mesh.
- Also very fine mesh needed at butterfly valve and filter section.
- Code-to-code comparison carried out; separation behaviour checked.

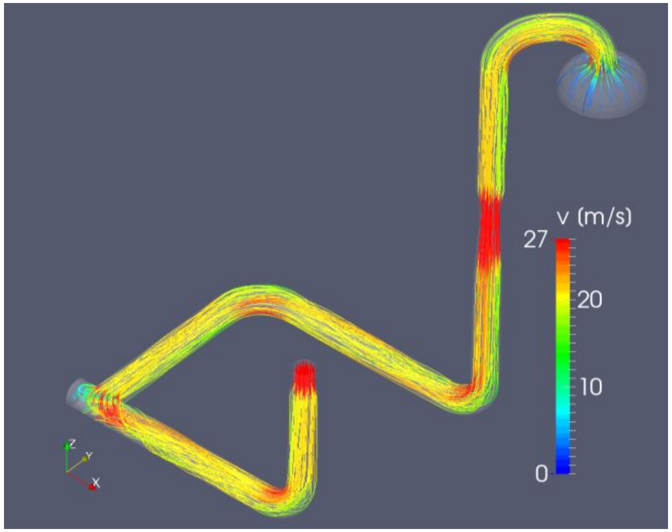


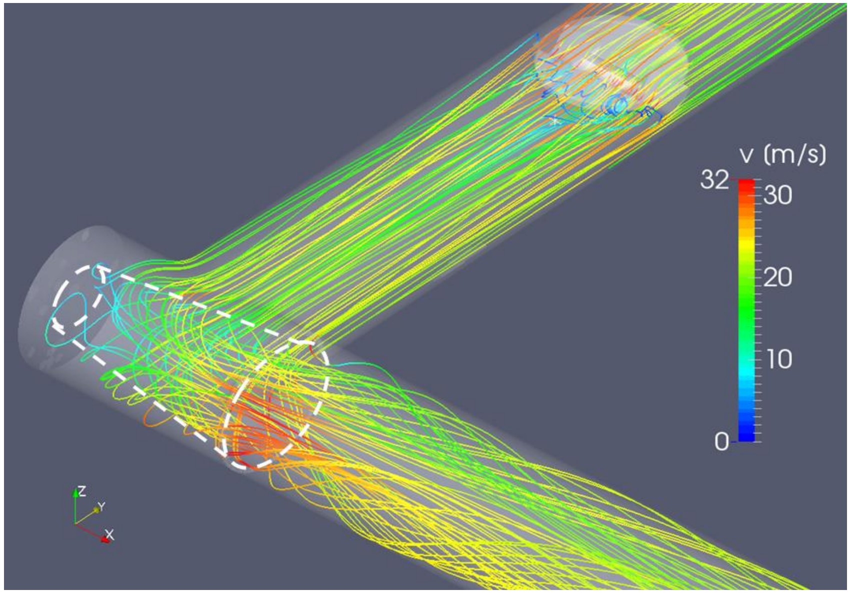


RCA rotor vibrations

2. CFD analysis - results.

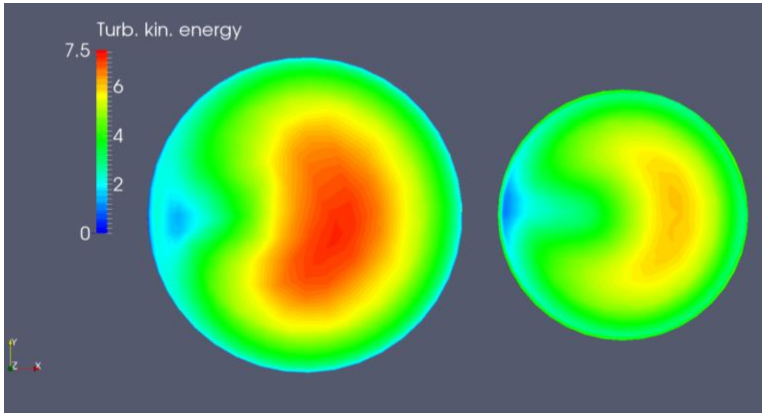
- Filter dominant obstacle:
  - Imposing the main pressure drop.
  - Redirection of flow at large scale vortical structures and small scale turbulence.
- K.O. drum inflow turbulence no significant impact on flow topology.
- Generally no flow separation.

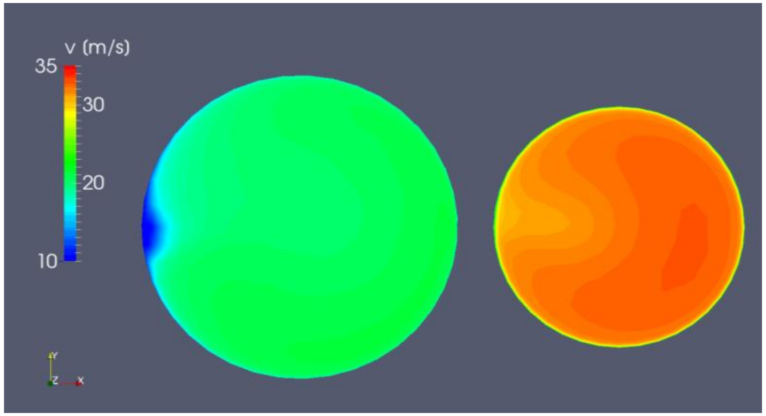


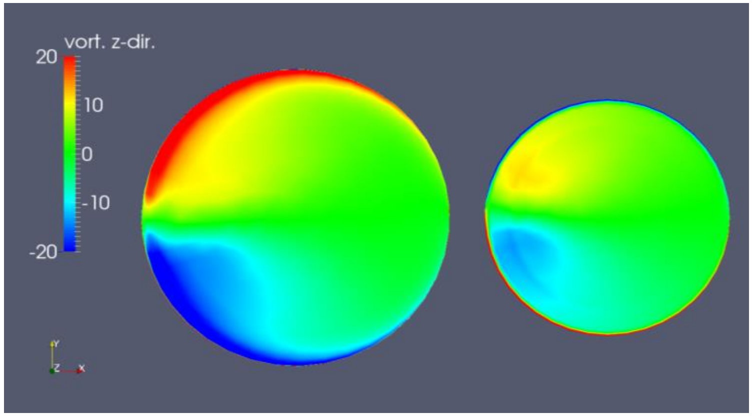


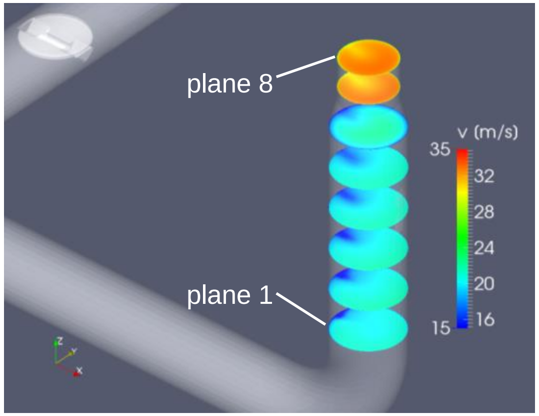
RCA rotor vibrations

2. CFD analysis - Compressor inlet conditions; velocity, turbulence kinetic energy and vorticity (z-direction).









Only weak, counter rotating vortices at the inlet.

Conclusions

- Design philosophy did not consider ***Flow Induced Pulsations (FIPs)***.
- Improved pipe supports reduced vibrations but do not eliminate the source.
- Rotor instability mainly caused by liquid carry over K.O. drum to compressor inlet.
- No fluctuating swirling flow into the compressor, mainly due to pressure drop over filter and high Reynolds number flow.
- Rotor most likely too susceptible for disturbances. Not critical anymore, but additional improvements planned.

Lessons learned

- FIPs can cause serious vibration problems at low frequencies.
- A pulsation and vibration analysis for this large diameter pipe systems should be part of the design.
- 3D pipe bend configuration in the suction piping can lead to flow distortion. To avoid this long radius bends should be applied or guide vanes could be installed in the bends.
- Take actual inlet flow into account in rotor damping (seals) and stiffness (bearing clearance) design.

Thank you for your attention!

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